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Conceptual Design of an Adjustable Venturi for Hydrodynamic Cavitation in Food Processing Optimization and Bioactive Compound Recovery

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Abstract

Hydrodynamic cavitation is attracting increasing interest in food processing as a non-thermal approach for preserving product quality and supporting the recovery of valuable bioactive compounds. Conventional Venturi devices are usually designed for fixed operating conditions, whereas real process streams may vary in temperature, viscosity, and gas or solid content. This can make it difficult to maintain stable and effective operating conditions when a fixed geometry is used. In this work, an adjustable circular Venturi is presented as a simple conceptual device for hydrodynamic cavitation in food applications. The external body and pipeline connections remain unchanged, while the throat section can be adjusted to adapt the device to different process requirements. In this sense, the proposed concept may also serve as an adjustable platform for exploring different operating conditions and identifying suitable throat configurations for specific food matrices and process targets. Once identified, such conditions may support the definition of a dedicated final Venturi configuration for the intended application. The proposed concept may be of interest for applications such as green extraction, food by-product valorization, and mild processing strategies aimed at preserving or enhancing bioactive compounds. This study is presented as a conceptual design contribution for food applications.

Keywords: hydrodynamic cavitation; adjustable Venturi; food processing; process optimization; bioactive compound recovery; green extraction

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1. Introduction

Hydrodynamic cavitation is commonly generated in industrial plants by static devices designed for a specific operating condition, most often circular-throat Venturi devices [1–3]. In real processes, however, the properties of the processed medium may change over time because of variations in temperature, viscosity, and gas or solid content [4–7]. When the device geometry remains fixed, maintaining stable and effective cavitation conditions over extended operating periods may become difficult.

In recent years, hydrodynamic cavitation has attracted growing interest as a promising non-thermal technology for food processing and other sustainable applications [8–10]. In the food sector, it has been considered for process intensification, green extraction, and the valorization of plant materials and agri-food by-products [8,9]. This interest is mainly related to the possibility of improving process efficiency while reducing severe thermal damage to sensitive compounds, including valuable bioactive molecules.

The effectiveness of hydrodynamic cavitation depends not only on operating conditions, but also on the geometry of the cavitation device [11–13]. However, most Venturi-based systems used in practice are designed with a fixed internal configuration. This may limit their flexibility when different products, feed compositions, or processing targets are involved. From a practical point of view, the most suitable operating condition is often identified during commissioning, when the actual

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properties of the feed and the constraints of the plant can be directly evaluated against process targets such as extraction yield, product quality, selectivity, or limited degradation.

For this reason, a cavitation device with a simple in-line adjustable constriction may offer useful additional flexibility during both process set-up and operation [14–17]. An adjustable configuration could help the operator adapt the cavitation effect to different process requirements without changing the external body of the device or modifying the existing plant connections [14–17].

In this work, a Dynamic Circular Venturi (DCVA) is presented as an adjustable circular Venturi for hydrodynamic cavitation in food applications. The external body and plant interfaces remain unchanged, while the throat section can be adjusted during operation in order to adapt the cavitation effect to different processing needs. In this sense, the DCVA is conceived not only as an adjustable cavitation device, but also as a practical tool for exploring different throat openings and identifying the most suitable operating condition for a specific matrix, process objective, or bioactive recovery target. Once such a condition has been identified, it may provide a rational basis for the design of a dedicated final Venturi configuration for the intended application. The proposed concept is intended as a simple design contribution for applications such as green extraction, food by-product valorization, and mild processing strategies aimed at preserving or enhancing bioactive compounds [9,10].

2. Adjustable Venturi Concept

A The Dynamic Circular Venturi (DCVA) is proposed as an adjustable circular Venturi for hydrodynamic cavitation in food applications. The concept is based on the possibility of modifying the internal throat section during operation, while preserving the external body and the plant connections unchanged. In this way, the device can be installed in-line in a manner comparable to a conventional Venturi, but with the additional advantage of a controllable internal constriction [14–20]. This feature is particularly relevant when the treated medium does not remain constant over time and when different process conditions require different cavitation effects [10].

In practical food-processing operations, the characteristics of the processed liquid may vary because of changes in composition, temperature, viscosity, or the presence of dissolved gas, suspended particles, or fine solid fractions [6,7]. Under these conditions, a fixed-geometry Venturi may not always provide the most suitable cavitation regime for the intended process target [11,18–20]. A device with an adjustable throat may therefore offer greater flexibility, since it allows the constriction to be adapted without replacing the unit or modifying the surrounding plant layout. This may be useful during process set-up, during commissioning, or when the same line is used for products or feed streams with different characteristics.

Within this perspective, the adjustable throat is intended to enable experimental screening of different cavitation conditions, so that the opening associated with the most appropriate balance between process intensity, selectivity, and product quality can be identified for a given application.

The operating principle of the DCVA is simple. The device is defined by a minimum throat diameter, d, corresponding to the most constricted configuration, and by a maximum throat diameter, D, corresponding to the most open configuration. During operation, the equivalent throat diameter, d_e, can vary between these two limits. To describe this adjustment in a simple and continuous form, a dimensionless opening parameter, χ, is introduced, where $\chi = 0$ identifies the minimum-throat configuration and $\chi = 1$ identifies the maximum-throat configuration. The equivalent throat diameter can then be expressed as

$$d_e = d + \chi\,(D - d) \qquad (1)$$

Equation (1) provides a simple description of the adjustable character of the device and is sufficient for the purposes of the present conceptual study. When the throat opening is reduced, the local flow acceleration through the constriction is expected to increase, leading to a more intense cavitation effect [12,13,21,22]. Conversely, when the throat opening is increased, the cavitation regime

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is expected to become milder [21,22]. In this way, the device offers a practical means of adapting the cavitation action to different process requirements.

From an application point of view, this adjustable configuration may be of interest in food-processing scenarios where the desired effect depends on the balance between process intensity and product quality. In some cases, a stronger cavitation action may be useful to promote extraction or disruption phenomena, whereas in other cases a milder condition may be preferable to avoid excessive degradation of sensitive compounds. The possibility of modifying the throat opening during operation therefore introduces an additional degree of practical flexibility, while keeping the overall device concept simple.

Once this operating condition has been identified, it may provide a rational basis for the design of a dedicated final Venturi configuration for the target process.

The DCVA is intended as a conceptual design contribution for food applications in which hydrodynamic cavitation may support green extraction, food by-product valorization, and mild processing strategies aimed at preserving or enhancing bioactive compounds. The value of the concept lies in the combination of in-line applicability, geometric simplicity, and adjustable operation. Rather than being restricted to a single nominal condition, the device is conceived as a Venturi-based cavitation module that can be adapted to different process needs while maintaining the same external installation layout.

3. Device Architecture

The proposed device is an adjustable circular Venturi in which the internal throat section can be varied during operation while the external body and the inlet and outlet interfaces remain unchanged. The purpose of this configuration is to allow modulation of the internal constriction without requiring modifications to the surrounding piping system. In this way, the device is conceived as an in-line Venturi module with a variable internal passage and a fixed external installation layout.

The architecture is based on an outer cartridge and an internal reconfigurable system that defines the wetted flow surface. As shown in the figures, three main functional elements can be identified. The first is the external actuation system, represented by the blue pistons arranged radially around the cartridge. These actuators operate in a coordinated manner and are associated with a single opening parameter, χ, which describes the geometric state of the device. The second element is the internal kinematic cage, represented by the white and gray components, which receives the imposed displacement from the external actuation system and transfers it to the internal retaining elements. The third element is the deformable liner, represented in red, which forms the internal wetted surface of the Venturi and allows the throat section to vary while maintaining continuity of the flow passage.

The deformable liner is described as a single-piece elastomeric component forming the internal surface in contact with the process fluid. In the present conceptual study, the liner material and detailed sizing are not further specified, since these aspects depend on the final application, the processed medium, and the corresponding design requirements. The liner is constrained by retaining rings connected to the internal structure. This arrangement is adopted so that the variation of the throat section is guided by the internal mechanism while preserving continuity of the internal profile during reconfiguration.

Within the proposed configuration, the equivalent throat diameter varies between the minimum value d and the maximum value D, as introduced in the previous section. The geometric state of the device is therefore identified by the equivalent throat diameter d_e, while the throat opening is regulated through the single dimensionless parameter χ, according to Equation (1). This is the defining feature of the architecture considered here: the internal geometry is varied through a single opening parameter directly associated with the throat section.

The throat region is also characterized by an axial length, L_t, which is kept constant by design. During operation, the geometry changes through the variation of the equivalent throat diameter, whereas the throat length remains unchanged. The proposed configuration therefore modifies the

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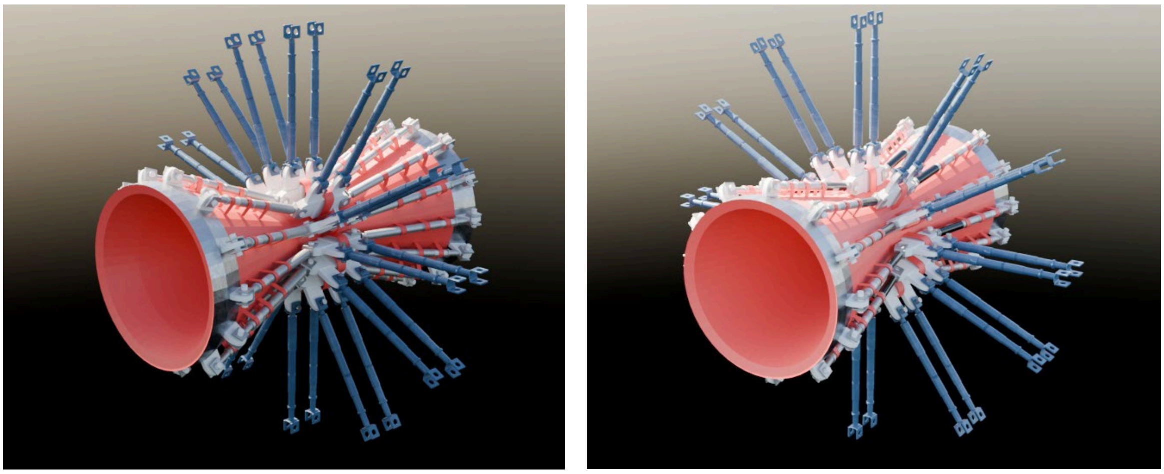
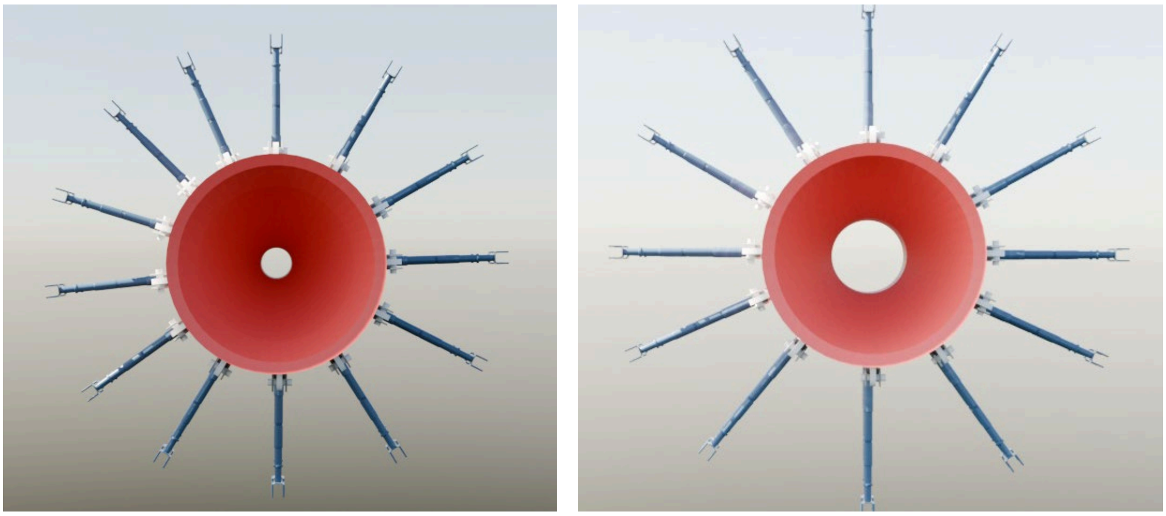
internal constriction through a controlled variation of the throat opening without introducing additional independent geometric variables. The geometry is consequently described in a simple manner, consistent with the conceptual nature of the present work.

Figures 1 and 2 show the two limiting configurations of the device. In the minimum-opening condition, the equivalent throat diameter is equal to d, corresponding to the most constricted internal passage. In the maximum-opening condition, the equivalent throat diameter is equal to D, corresponding to the most open internal passage. In both cases, the outer body and the piping interfaces remain unchanged, while only the internal flow passage is modified. These figures therefore illustrate the central design feature of the proposed device, namely the possibility of varying the internal throat section within a fixed external geometry.



(a) (b)

Figure 1. Schematic view of the proposed adjustable Venturi in the two limiting configurations: (**a**) minimum equivalent throat diameter, $d_e = d$; (**b**) maximum equivalent throat diameter, $d_e = D$. The blue pistons represent the external actuation system, the white/gray components represent the kinematic cage, and the red element represents the deformable liner forming the internal wetted surface.

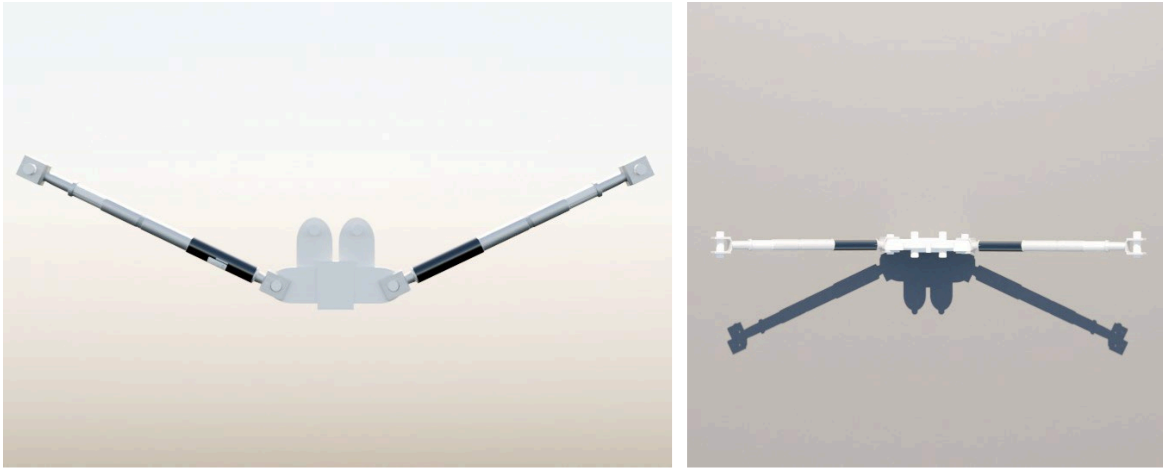


(a) (b)

Figure 2. Schematic front view of the proposed adjustable Venturi in the two limiting configurations: (**a**) minimum throat opening, $d_e = d$; (**b**) maximum throat opening, $d_e = D$. The external interfaces remain unchanged, while the internal passage varies.

Figure 3 shows the elementary module used to form the internal kinematic cage. The complete cage is obtained by circumferential repetition of this module around the device axis. This representation is useful because it clarifies how the internal mechanism is organized and how the imposed displacement is distributed around the circumference.

The number of repeated modules, indicated as N_{θ}, defines the circumferential discretization of the support system acting on the liner. In conceptual terms, a larger number of modules corresponds to a denser circumferential support of the deformable liner, whereas a smaller number corresponds to a more widely spaced support arrangement. In the present work, this aspect is reported only as a descriptive element of the architecture.



(a) (b)

Figure 3. Schematic elementary module of the internal kinematic cage: (**a**) front view; (**b**) top view. The complete cage is obtained by circumferential repetition of the elementary module.

Figure 4 shows the longitudinal section of the device and clarifies the internal transfer of motion from the actuation system to the deformable liner. The longitudinal view highlights the continuity of the internal surface and the variation of the throat section produced by the coordinated motion of the internal mechanism.

During operation, the external actuators impose a displacement on the kinematic cage; the cage transfers this displacement to the retaining structure; the liner then deforms accordingly; and the equivalent throat diameter changes within the available geometric range. Throughout this process, the external body and the piping interfaces remain fixed.

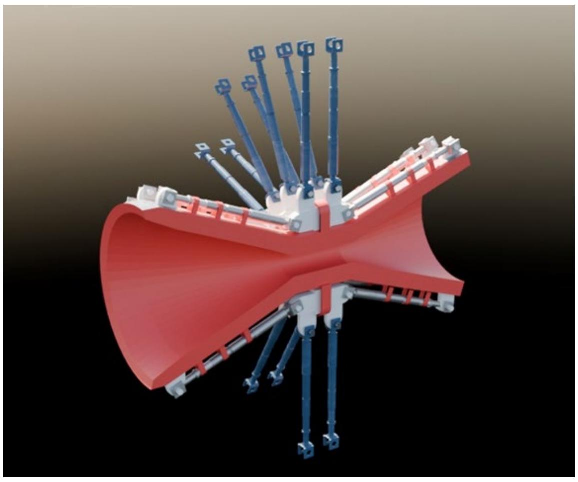


Figure 4. Schematic longitudinal section of the proposed adjustable Venturi. The deformable liner forms a continuous internal surface, while the internal actuation mechanism modifies the equivalent throat diameter.

The operating principle of the device can therefore be described in a direct way. When the opening parameter χ is reduced, the internal throat section moves toward the minimum configuration and the equivalent throat diameter approaches d. When χ is increased, the internal passage becomes wider and the equivalent throat diameter approaches D. The geometry of the device is thus varied through a single opening parameter, while the external installation remains unchanged. In this sense, the proposed architecture combines internal geometric adjustability with in-line integration.

Overall, the device architecture presented here describes an adjustable circular Venturi in which the wetted internal surface is reconfigured through the coordinated action of an external actuation system, an internal kinematic cage, and a deformable liner. The result is a variable throat section within a fixed outer body, described through a single opening parameter and represented by the equivalent throat diameter.

4. Potential Food Applications

The proposed adjustable Venturi concept may be of interest in food-processing applications where hydrodynamic cavitation is used as a non-thermal approach and where the characteristics of the treated medium may change according to the raw material, formulation, or processing stage [23–25]. In these situations, the possibility of modifying the internal throat section may provide a more flexible operating condition than that offered by a fixed-geometry device.

One relevant area is the extraction of valuable compounds from plant-based materials. Many food matrices contain bioactive substances such as phenolic compounds, pigments, antioxidants, and other functional molecules that may be recovered for nutritional, technological, or commercial purposes. Since these matrices can differ markedly in composition, particle content, viscosity, and structural resistance, a device with an adjustable throat opening may be useful when different processing conditions are required for different materials.

In this context, the DCVA may be used to determine the throat opening most suitable for maximizing the recovery of selected bioactive compounds from a given matrix while limiting excessive degradation of sensitive components.

A second area of interest is the valorization of agri-food by-products and side streams [26]. Residues derived from fruit, vegetable, cereal, or other food-processing operations often retain compounds of potential value, but their recovery may depend on the physical characteristics of the suspension and on the desired level of treatment intensity. In this context, an adjustable Venturi may represent a practical option for processing streams with variable properties while maintaining the same external installation layout.

The concept may also be relevant in food-processing conditions where a balance is required between treatment intensity and product quality [27]. In some cases, a more intense cavitation action may be desirable to promote disintegration, mass transfer, or compound release. In other cases, a milder condition may be preferable in order to limit excessive alteration of sensitive components [27]. The possibility of varying the throat opening may therefore be useful when the process objective is not simply to maximize intensity, but to identify a suitable operating condition for the specific product and application.

Additional interest may arise in processing lines handling different liquid foods, extracts, suspensions, or semi-complex feed streams within the same plant environment. Under these circumstances, the use of a fixed-geometry cavitation device may offer limited adaptability when the processed medium changes from one duty to another. An adjustable internal constriction may instead provide a simple way to accommodate such variability without altering the external configuration of the unit.

Overall, the proposed device may be considered for food applications involving hydrodynamic cavitation in which operational flexibility is desirable, particularly in relation to green extraction, by-product valorization, and processing strategies aimed at preserving or enhancing bioactive compounds [8,26].

Accordingly, the adjustable concept may be valuable not only for direct processing flexibility, but also as a preliminary optimization tool for defining application-specific operating windows in food systems.

These examples highlight the potential relevance of the proposed adjustable Venturi concept for food-processing applications involving hydrodynamic cavitation.

5. Advantages and Limitations

The proposed adjustable Venturi concept is based on a simple idea: a conventional in-line Venturi is typically characterized by a fixed internal geometry, whereas the device presented in this work introduces a variable internal throat section within an unchanged external body. This means that the inlet and outlet interfaces remain fixed, while the equivalent throat diameter can be modified during operation through a single opening parameter. From a process-design perspective, this is the central feature of the concept, because it combines in-line integration with internal geometric adjustability.

This aspect may be particularly relevant when hydrodynamic cavitation is applied under conditions in which the treated medium is not constant. In food-related processes, the composition of the fluid, its viscosity, the presence of suspended solids, and the overall physical response of the matrix may vary according to the raw material, formulation, or processing stage [4,5]. Under these conditions, a fixed-geometry Venturi may not always provide the same operating response [11,18–20]. The proposed architecture addresses this point by allowing the internal constriction to vary within the same installation layout, without requiring replacement of the device or modification of the surrounding piping system.

A first advantage of the concept is therefore its geometric adaptability within a fixed external envelope. A second advantage is its architectural simplicity. The geometric state of the device is described by the equivalent throat diameter and regulated through a single dimensionless opening parameter. This gives the concept a direct physical interpretation and avoids the introduction of multiple independent geometric variables. In the context of the present study, this simplicity is an important strength because it keeps the device easy to define at the conceptual level while still allowing controlled variation of the throat section between two limiting configurations.

A further advantage of the concept is its potential use as a process-development tool. By progressively varying the throat opening, the device may help identify the operating condition most suitable for a given matrix and process target, thereby supporting the definition of a fixed and application-oriented Venturi geometry for subsequent implementation.

Another relevant feature is the continuity of the internal wetted surface, which is obtained through the deformable liner and the associated internal kinematic structure. The device is therefore not described as a discontinuous internal assembly, but as a configuration in which the flow passage remains continuous while the internal constriction changes. This is an important point in the overall interpretation of the concept, because the operating principle is not based only on the presence of a variable opening, but also on the possibility of achieving that variation while preserving continuity of the internal passage.

From the perspective of possible food applications, the concept may be of interest wherever hydrodynamic cavitation is used under variable process conditions or where a balance is required between treatment intensity and preservation of product quality [23–27]. In this sense, the proposed adjustable Venturi may be considered for operations involving green extraction, agri-food by-product valorization, and processing strategies aimed at preserving or enhancing bioactive compounds. Its potential relevance lies in the possibility of adapting the internal throat section to different process needs while maintaining a simple in-line device configuration.

At the same time, the present study has clear limitations that should be stated explicitly. First, the work is conceptual in scope and is focused on the definition of the device architecture and its operating principle. It does not include a detailed mechanical design, an application-specific sizing procedure, or a full engineering development of the actuation system and deformable components.

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As a consequence, the paper should be read as a conceptual design contribution rather than as a finalized device design.

A further limitation is the absence of experimental validation on real food systems. The study therefore does not quantify the effect of throat adjustment on extraction yield, preservation performance, product quality, or recovery of bioactive compounds. These outcomes would necessarily depend on the specific process, the treated matrix, and the final implementation of the device.

Within such a development pathway, the adjustable prototype could be used to identify the relevant working condition, whereas the final industrial solution could then be implemented through a dedicated food-grade Venturi specifically designed for the selected application. In the same way, the present work does not address in detail aspects such as liner durability, hygienic compatibility, cleaning procedures, or long-term operation under repeated use, all of which would be relevant in a practical application-oriented development.

Overall, the proposed device should therefore be interpreted as a conceptual adjustable Venturi architecture for hydrodynamic cavitation in food applications. Its main contribution lies in the definition of a simple in-line configuration with fixed external interfaces and a variable internal throat section described through a single opening parameter. Within this scope, the concept provides a clear and coherent basis for considering adjustable Venturi-based hydrodynamic cavitation as a possible option in food-processing applications.

6. Conclusions

This work presents the conceptual design of an adjustable circular Venturi for hydrodynamic cavitation in food applications. The proposed device preserves the external body and the inlet and outlet interfaces of a conventional in-line Venturi, while allowing the internal throat section to vary during operation. Its geometry is described through the equivalent throat diameter and a single opening parameter, providing a simple and direct representation of the adjustable nature of the concept.

The proposed architecture combines an external actuation system, an internal kinematic cage, and a deformable liner forming the internal wetted surface. Through the coordinated action of these elements, the throat section can vary between a minimum and a maximum configuration while the external installation layout remains unchanged. This is the central feature of the device and the main aspect distinguishing it from a fixed-geometry Venturi.

Within the food sector, the concept may be of interest wherever hydrodynamic cavitation is applied under variable process conditions or where different matrices and processing targets require different cavitation effects. In this perspective, the proposed adjustable Venturi may be relevant for applications related to green extraction, agri-food by-product valorization, and processing strategies aimed at preserving or enhancing bioactive compounds.

Beyond its value as an adjustable cavitation device, the DCVA may also be regarded as a useful conceptual and experimental platform for identifying suitable operating conditions for specific food matrices and process objectives. By enabling the exploration of different throat openings, the concept may help determine the working condition most appropriate for balancing process intensity, selectivity, and product quality. Once identified, this condition may provide a rational basis for the development of a dedicated final Venturi configuration for the intended application.

Within the scope of the present study, the work is presented as a conceptual design contribution. Its main result is the definition of a simple adjustable Venturi architecture for in-line hydrodynamic cavitation, described in terms of geometry and operating principle and oriented toward possible food applications. Future developments should include application-specific engineering design and experimental validation on real food systems in order to assess the practical relevance of the concept and its potential translation into dedicated food-grade process equipment.

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Abbreviations

The following abbreviations are used in this manuscript:

DCVA	Dynamic Circular Venturi

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